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Solar Energy 86 (2012) 369–378

SOLAR ENERGY

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Solar hybrid systems with thermoelectric generators

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Received 24 May 2011; received in revised form 9 September 2011; accepted 10 October 2011
Available online 11 November 2011

Communicated by: Associate Editor Bibek Bandyopadhyay

Abstract

The possibility of using of thermoelectric generators in solar hybrid systems has been investigated. Four systems were examined, one working without radiation concentration, of the traditional PV/Thermal geometry, but with TEGs between the solar cells and heat extractor, and three other using concentrators, namely: concentrator – TEG – heat extractor, concentrator – PV cell – TEG – heat extractor, and PV cell – concentrator – TEG – heat extractor. The TEGs based on traditional semiconductor material Bi_2Te_3 and designed for temperature interval of 50–200 °C were studied experimentally. It was found that the TEG's efficiency has almost linear dependence on the temperature difference ΔT between its plates, reaching 4% at $\Delta T = 155$ °C (hot plate at 200 °C) with 3 W of power generated over the matched load. The temperature dependencies of current and voltage are also linear; accordingly, the power generated has quadratic temperature dependence. The experimental parameters, as well as parameters of two advanced TEGs taken from the literature, were used for estimation of performance of the hybrid systems. The conclusions are drawn in relation to the efficiency at different modes of operation and the cost of hybrid systems, as well as some recommendations in relation to optimal solar cells for applications in these systems.

Keywords: Solar hybrid system; Thermoelectric generator; Solar radiation concentration; Photovoltaic panel; Efficiency electrical and thermal

1. Introduction

It is generally accepted that the hybrid solar systems have higher efficiency and stability of performance in comparison with individual solar devices, that explains the current interest towards them. The simplest of these systems (and the most widely used and studied – see, for example, publications by Zontag (2006, 2008); Tripanagnostopoulos (2007); Zakharchenko et al. (2004); Robles-Ocampo et al. (2007); Ibrahim et al. (2011)) is the PV/Thermal (PVT) system consisting of photovoltaic (PV) panel coupled to heat extractor with running water or air. The major part of the PVT systems uses crystalline Si solar PV module (PVM) with conversion efficiency of around 14%, taking advantage of its cooling by heat extracting/generating unit (plane collector), producing 100–140 W/m^2 of electric energy at peak illumination, and about four times as much thermal energy stored in water/air, heated up to 45–50 °C.

The electric energy generation in PVT systems is the most important; to have higher efficiency of the PVM, the temperature of adjacent plane collector has to be relatively low which means low thermal efficiency of the system. To have both efficiencies high, we proposed (see paper by Zakharchenko et al. (2004)) to cover by PVM only initial part of the heat collector; later the constructions of this kind appeared in other projects (Zontag, 2006; Dubey and Tiwari, 2008). It is also possible to employ in PVT the bifacial PV modules with higher electrical efficiency (Luque et al., 1980; Robles-Ocampo et al., 2007).

Another possibility to increase the electricity production in PVT is to put the heat flux originating between PVM and heat extractor through thermoelectric generator

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doi:10.1016/j.solener.2011.10.020

Nomenclature

A	surface area (m^2)
B	total irradiation power at active element in concentrated sunlight (W)
C	degree of concentration of solar radiation
E_g	the band gap of semiconductor material (eV)
I	solar radiation intensity (W/m^2)
P	power (W)
R	reflection coefficient
R_{heat}	thermal resistance (the ratio of temperature difference to thermal flux (K/W))
T	temperature (K)
ΔT	temperature difference (K)
Z	optimized thermoelectric figure of merit (K^{-1})
ZT	dimensionless thermoelectric figure of merit
h	convection coefficient (W/m^2)
k	the ratio of the real emissivity to that of an ideal black body ("blackness degree")
α	quality coefficient of the radiation concentrator
β	heat loss coefficient of an active element in concentrated sunlight
γ	temperature coefficient of the solar cell efficiency (K^{-1})
η	solar cell efficiency
η^*	efficiency of thermoelectric generator
η_0	Carnot efficiency
σ	the Stephen–Boltzmann constant (W/m^2K^4)

(TEG) or some other heat engine. Rough estimation of the possible increase of efficiency could be made on the basis of that for Carnot cycle: with an average temperature difference between PVM and heat extractor of 30 K and the ambient temperature of 300 K it is 10% which is comparable with the efficiency of PV module itself. Half of this figure (that could be achieved with Stirling engine) will be also essential. TEGs nowadays have lower efficiency, but the latest development in this field (see, for example, Venkatasubramanian et al., 2001; Tavkhelidze et al., 2002; Bulat et al., 2010) shows that the use of new materials (nanostructured ones in particular) can greatly enhance it. On the other hand, TEGs could be incorporated in solar hybrid system in many different ways.

Application of TEGs for solar energy conversion has been studied both theoretically and experimentally by Omer and Infield (1998). Later (Vorobiev et al., 2006a) we proposed two different constructions of the hybrid systems consisting of PVM and TEG or heat engine where radiation concentration was also used: in one of them both PVM and TEG are illuminated by concentrated sunlight, in another the light transmitted by PVM is concentrated onto TEG. It was shown that in both cases essential increase of electrical efficiency could be gained. Kraemer et al. (2008) developed a general optimization methodology for similar hybrid systems.

Recently Peng et al. (2010) performed the detailed experimental and theoretical analysis of solar concentration system using TEG, with specific recommendations about the necessary concentration degree and the different materials for TEG, including the ones most recently developed, in a wide temperature range (up to 800 K). All these publications show that TEGs could be successfully used in different solar energy conversion systems.

The aim of this paper is the investigation of performance of several hybrid systems producing electric and thermal energy with application of TEGs and working in non-concentrated as well as concentrated solar radiation, at relatively low temperatures (not higher than 250 °C). Some of the systems studied include traditional Si PV modules, either crystalline or amorphous ones. The main producers of commercial TEGs (USA, Russia, China) use bismuth telluride as basic semiconductor material for these temperatures, so we employed typical samples of this kind; the parameters necessary for discussion were found experimentally, and the cost-efficiency estimation in some cases was made. Taking into account the current investigations in the field of new materials for TEGs, we also made estimations of the possible effect of these advanced TEGs materials on the efficiencies of the hybrid systems. It is shown that some of the systems discussed could be useful already with existing elements; the other could become practical if the new TEGs and PVMs based on materials with certain specified properties will be developed.

2. Description of the different geometries of solar hybrid systems with TEGs

2.1. A system with TEGs between PVM and heat collector

Here we consider a system with traditional PVT design where TEGs are introduced between the PV module (PVM) and heat extractor (water filled plane collector), so that heat generated under illumination in each PV cell passes through individual TEG that has good thermal contact with this cell from one side, and with heat extractor from the other side. The general scheme is presented in Fig. 1. Here, the direct sunlight falls onto a PV panel where each individual cell (1) possesses a back electrode (2) with high thermal conductivity, having direct thermal contact with the hot plate of corresponding TEG (3 and 4) first part of plane heat collector which main purpose is to absorb the heat flux from PV cells passing through TEGs, (5) second part of the heat collector which directly absorbs solar radiation and is necessary to get the water temperature appropriate for its domestic (or other) usage; (6) is the hot water

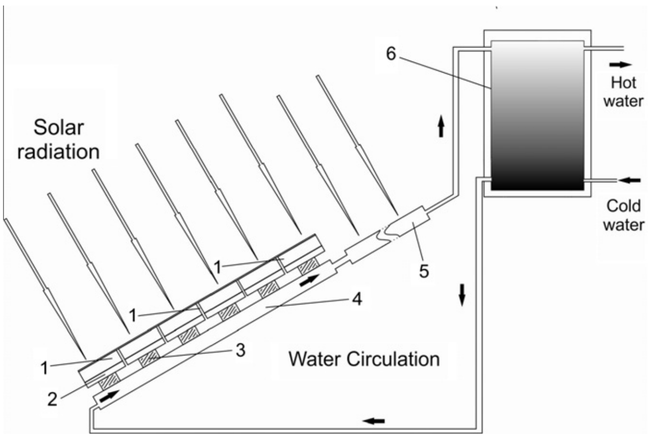

Fig. 1. A scheme of hybrid PV/T system with TEGs, non-concentrated radiation. (1) – solar cell, (2) – cell's back electrode, (3) – TEG, (4) –heat extractor, (5) – plane collector, (6) – thermal tank.

tank. It is evident that this system with collector divided in two parts is, in principle, equivalent to a scheme with one collector where PVM covers its initial part corresponding to the entrance of cold water/air. Such schemes were realized and studied in papers by Zakharchenko et al. (2004); Zontag (2006), and Dubey and Tiwari (2008). The orientations of the system's elements in relation to the Sun as well as the working conditions of second collector (5) and water tank (6) are not different from those in traditional systems; therefore we shall analyze here only energy transformation in the new part: PVM–TEGs-heat extractor (1–4 in Fig. 1).

For solar radiation intensity I, solar cell reflection coefficient R and cell's efficiency η, the electric power generated is $P_e = \eta I(1 - R)A$, and the heat power generation P within one cell will be defined by the relation

$$P = I(1 - R)(1 - \eta)A \tag{1}$$

Here A is the cell area. Cell efficiency η is a function of temperature, but for relatively small differences between cell's equilibrium temperature T and the ambient temperature T_a this dependence could be neglected. The value of T is determined by the balance of the heat power generation and all the heat losses: by convection, by radiation, but mainly by heat extraction through back contact with adjacent TEG. The corresponding balance equation will be:

$$P = [h(T - T_a) + \sigma k(T^4 - T_a^4)]A + (T - T_4)/R_{heat} \tag{2}$$

Here h is the convection coefficient (in case of natural convection in air, $h \approx 5$–$10\ \mathrm{W/m^2}$), $\sigma = 5.67 \times 10^{-8}\ \mathrm{W/m^2K^4}$ – the Stephan–Boltzmann coefficient for blackbody radiation, k is the "blackness degree" of solar cell's surface, and R_{heat} is the TEG's thermal resistance; T_4 is the temperature of the plane collector 4 which depends, first of all, on the input water temperature and the water flux. In these equations we neglect the thermal gradients in PV cell and plane collector. For the efficient performance of the TEG and plane collector, the last term in (2) should be dominant. Later we shall see that this condition is usually fulfilled.

The additional electric power P^* generated by TEG will be defined by the last member in (2) multiplied by the TEG's efficiency η^*:

$$P^* = \eta^*(T - T_4)/R_{heat}.$$

The dependence of η^* upon the working conditions and the materials parameters was discussed in our publications in 2006.

Thus the total electric power generated by one pair "Solar Cell + TEG" will be

$$P = P_e + P^* = \eta I(1 - R)A + \eta^*(T - T_4)/R_{heat}. \tag{3}$$

We can take as reasonable approximation that the total heat flux passing through TEG is finally absorbed by the plane collector 4 (Fig. 1), pre-heating the passing water. The water final temperature will be determined by the second part (5 in the figure) of the collector, which should be designed in the manner necessary to provide the temperature needed for application planned. For the TEG's efficiency we shall use the expression

$$\eta^* = \eta_0 \frac{\sqrt{1 + ZT_M} - 1}{\sqrt{1 + ZT_M} + T_c/T_h} \tag{4}$$

Here Z is the optimized thermoelectric figure of merit for the TEG, ZT_M is dimensionless thermoelectric figure of merit with T_M being an average TEG temperature, T_c and T_h are the temperatures of the cool and hot TEG's plates correspondingly. The coefficient η_0 is the Carnot efficiency: $\eta_0 = \Delta T/T_h = 1 - T_c/T_h$, here $\Delta T = T_h - T_c$. It is evident that for the system discussed, $T_c = T$, and $T_h = T_4$ (for the details, see Vorobiev et al., 2006a). We note that in the abovementioned paper by Kraemer et al., 2008, the expression used for calculation of the TEG's efficiency is almost identical to (4), but the term "−1" in numerator is absent. We believe that our expression (4) is physically correct because it gives the zero efficiency for $ZT = 0$ (it is not so without "−1" term), and increase of efficiency with an increase of Z and ΔT.

2.2. Concentrating hybrid systems with TEG

As it was mentioned, two hybrid systems with solar radiation concentration and high temperature stage were discussed in general terms in our previous paper (Vorobiev et al., 2006a). Here we shall present the estimations of performance of these systems introduced earlier, for the cases of c-Si and a-Si PV modules with a specific TEG as the high temperature stage (see below) as well as of the system that includes only concentrator and TEG; for our analysis, the results obtained in the previous works will be used. Fig. 2 gives schematic presentation of all three geometries: the TEG with heat extractor at the back surface illuminated with concentrated solar light (a), PV panel in concentrated light with TEG behind it (b) and TEG in concentrated radiation which passes through the PV panel (c). In all

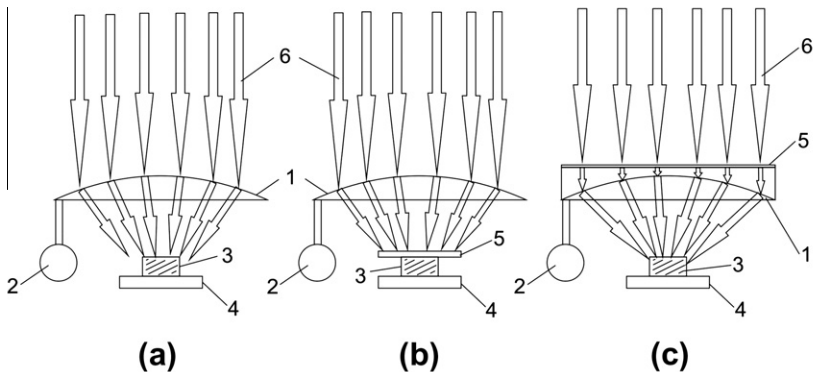

Fig. 2. Schemes of hybrid systems with TEG and concentrated Sun radiation.

cases, concentrator is shown as lens 1, it is bound to the Sun tracking system 2 (see Vorobiev and Vorobiev, 2010), TEG is denoted as 3 and 4 is the heat extraction system, 5 – the PV panel, and 6 – solar radiation. As in the previous case 2.1, the heat extractor used in all three systems can provide water (or air) heated to 40–50 °C for domestic applications.

In the schemes of Fig. 2, the radiation concentrator is represented by traditional lens. It is evident that other concentrating devices could be employed, like Fresnel lens or parabolic mirror. Fig. 3 presents a scheme of the type "a" system with parabolic mirror (1) that we constructed for one of our experiments. Here TEG is denoted as 3, and heat extractor – 2; 4 – the incoming solar radiation. Clearly, this design could be used for the other systems as well.

It must be mentioned (see Zakharchenko et al., 2004) that a PV panel for the hybrid system should be elaborated in a special way, providing high thermal conductivity of the substrate and having no surface roughness that is usual for traditional panels: instead of roughness, the antireflection coating must be used, but no light dissipation is acceptable. For the efficiency of these PV panels we shall use average data from the literature, based on their structure and the corresponding material properties.

In calculations of the energy balance of the elements working in concentrated radiation flux, the optical losses

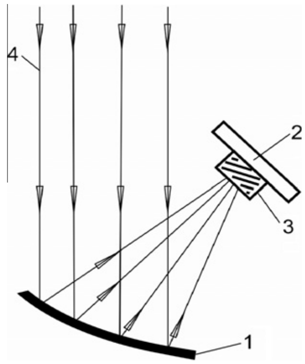

Fig. 3. TEG (3) with heat extractor (2) in radiation concentrated by parabolic mirror (1).

in concentrator will be characterized by his quality coefficient α (so that the actual losses will be equal to $1 - \alpha$), and the heat losses in the illuminated element by the coefficient $\beta < 1$ which was calculated in paper of Vorobiev et al. (2006b), and is written as

$$\beta = 1 - \frac{[h(T - T_a) + \sigma k(T^4 - T_a^4)]}{\alpha CI} \tag{5}$$

This coefficient in an obvious manner takes into account convection and radiation losses (see (2) where the main notations are the same as here); C is the concentration degree. Thus in estimation of the working conditions of the element under concentrated sun light, the actual intensity on this element will be equal to $\alpha\beta CI$.

3. Experimental studying of TEGs

In our experiments we use thermoelectric generators (TEGs) based on traditional material Bi_2Te_3, produced by Kryotherm (Saint Petersburg, Russia, website http://www.kryotherm.ru) of the type TGM-127-1.4-2.5, with the following basic parameters: dimensions $40 \times 40 \times 4.8\ mm^3$, electrical resistance at temperature interval 50–200 °C 3–4 of Ohm, thermal resistance $R_{heat} \approx 2.3$ K/W, efficiency at temperature difference between the plates of 100 K around 3%, with maximum power generated over the external matched resistance of around 1.5 W (voltage of about 2.4 V and current around 0.6 A). These data can be used for preliminary estimations; the final conclusions will be based upon the experimental parameters.

3.1. Equipment for measurements

In order to determine the working parameters of the TEG in different operating conditions, the following measuring equipment has been fabricated. It includes a heating plate, a cooling plate and a chassis (see the scheme and photograph in Fig. 4). The heating plate is a rectangular plate of aluminum with dimensions 100 mm × 100 mm × 3.175 mm. For heating up to temperatures below 100 °C, it was coupled to a water container which was heated with a 250 W resistance. For higher temperatures, a 1000 W hot

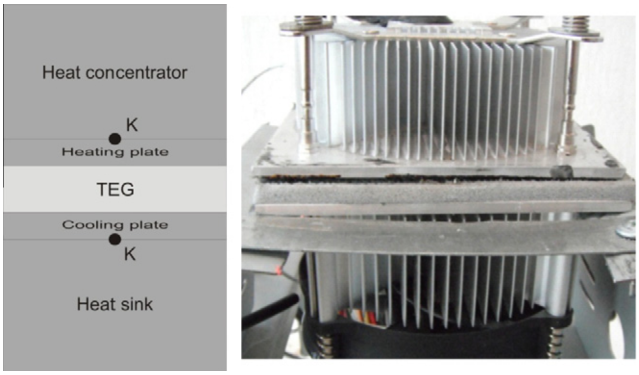

Fig. 4. Measurements equipment: a scheme (left) and photo (right).

air gun was used. The cooling plate was another Al plate of the same type. The heat flux concentrator was attached to the heating plate, and the heat sink – to the cooling plate. The thermocouples (Fluke 52 K/J thermometer, "K" in Fig. 4) were used to control the temperature gradient.

Before the measurements, both sides (ceramic plates) of the TEG were coated with a special compound providing good thermal contact with Al plates. To determine the maximum generated power, at each temperature difference between the plates of the TEG, the current and voltage on the variable load resistance were measured with the amper–voltmeter Fluke model 175.

3.2. Results and discussion

The typical results are presented in Fig. 5 as five sets of data corresponding to the different values of ΔT (the temperature difference across the TEG, shown by the figure): the lower set (squares) was obtained at $\Delta T = 36$ K, and the highest (rhombs) – at $\Delta T = 155$ K. For each fixed value of ΔT, the current and voltage were measured at six values of load resistance (from 0 to 5 Ω), their product giving the power dissipated in the resistance mentioned. The highest power generated at $\Delta T = 155$ K was around 3 W, i.e. two

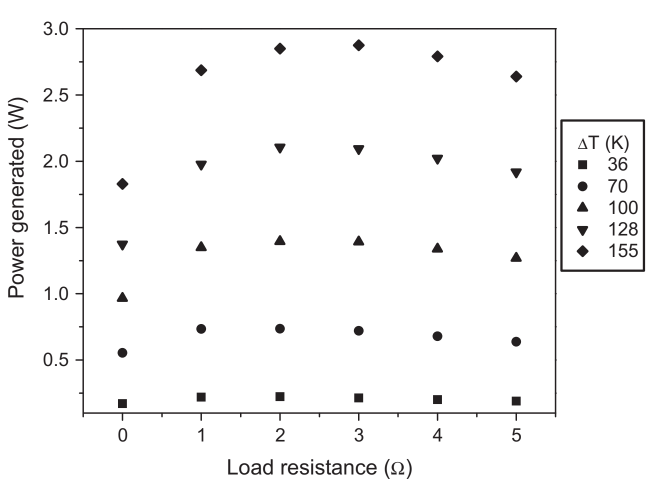

Fig. 5. Power generated by TEG at different temperature differences.

times larger than that given by producer for the value of $\Delta T = 100$ K. It agrees with our observation that both current and voltage produced by TEG are, in first approximation, proportional to ΔT.

It could be seen that for each temperature difference an optimal load exists (corresponds to the maximum of the power generated), which slightly shifts to higher values as the temperature grows. This effect is connected with the variation of the TEG's internal resistance (as it is well known, an optimum load must be equal to the internal resistance). For example, at $\Delta T = 100$ K, the optimum load is 2 Ω, whereas at 155 K it is 3 Ω. For the last case, the corresponding optimal voltage is around 3 V, and the optimal current approximately 1 A.

The next figure (Fig. 6) shows the main characteristics of the TEG's performance in function of temperature difference between its sides. TEG efficiency (Fig. 6a) is almost linear function of ΔT (as expected): Fig. 6a presents data obtained for the four different thermal compounds placed as a thin film between Al plates and the TEG's sides: Steren thermal compound (curve 1), Diamond compound (2), Manhattan (3) and Cooler Master THK-002 (4). The best results obtained in the last case, are in a good agreement with the manufacturer's data (as it was mentioned above, the efficiency at $\Delta T = 100$ K is 3%).

Fig. 6b shows the maximal current, voltage and power generated at each ΔT value. Whereas voltage and current grow with ΔT in almost linear manner, the power is approximately quadratic function. It clearly shows that TEGs more efficiently work at higher temperature difference: thus, at ΔT of order of 150 °C (hot plate is at 200, and the cool one at 50 °C), the experimentally measured efficiency is 4%; if we extrapolate the upper strait line in Fig. 6 up to $\Delta T = 250$ °C (there exists TEG of similar type with upper temperature limit of 300 °C), the expected efficiency will be 6.5%.

From expression (4) we find that the TEG's efficiencies measured correspond to the value of figure of merit ZT equal to 0.7; this value is typical for commercially available thermoelectric materials (Anatychuk and Bulat, 2001). The latest research in the field have shown that the value of ZT can be greatly enhanced using modern methods of nano-structurization; thus, paper of Venkatasubramanian et al. (2001), reports the value $ZT = 2.4$ obtained in thin film superlattices of Bi_2Te_3/Sb_2Te_3; some other examples were given by Vorobiev et al. (2006a) (in particular, the value of $ZT = 4$ reported by Tavkhelidze et al. (2002)).

4. Estimation of parameters of hybrid systems with TEGs

4.1. Hybrid system with non-concentrated sunlight

This system is presented in Fig. 1, and Eq. (2) describes the heat exchange between the system's main elements. First of all, let us make a rough comparison between the three terms in the right part of (2), using the values of coefficients given above, and assuming that the temperature

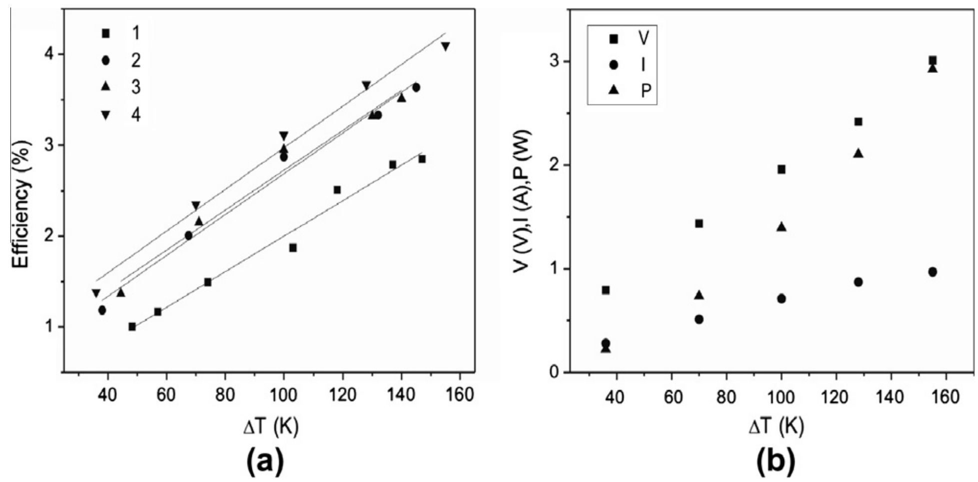

Fig. 6. (a) Results of measuring of TEG's efficiency with different thermal compounds. (Steren thermal – 1, diamond – 2, manhattan – 3 and cooler master THK-002-4). (b) Experimental dependencies of TEG's maximal current, voltage and power generated upon the temperature difference.

difference between the PV cell and the ambience that is approximately equal to the value of ΔT over the TEG, can be of order of 30–40 K. So, the first term has order of 200 W/m^2, and the total power lost by air convection for a cell with surface area of around 100 cm^2 will be approximately 2 W. The second term might be of the same order if we take for the "blackness" coefficient k showing how close could be a PV cell to a black body, value of 1. But in the case studied, when the temperatures of PV cell and the ambience are close to 300 K, the black body radiation corresponds to infrared spectral region (according to the Wien's law, the wavelength of maximum of this radiation at 300 K is approximately 10 μm); practically all semiconductor materials used for PV cells are transparent in this region, so this term can be neglected.

The last term in (2) for the TEG's thermal resistance of 2.3 K/W will be 13–15 W, much larger than the convection term value. Thus we see that the heat flux from PV cell to heat extractor through TEG will be dominating, that gives a basis for an efficient performance of TEG. Having combined Eqs. (1) and (2), and neglecting the second term in (2), we find the PV cell temperature:

$$T = \frac{[I(1-R)(1-\eta) + hT_a]A + T_4/R_{heat}}{hA + 1/R_{heat}} \tag{6}$$

Estimations according to (6) give the value of ΔT over the TEG not higher than 30–40 K (one must take into account that the real thermal resistance of TEG could be larger than the passport value of 2.3 K/W due to not-ideal thermal contact between the TEG's plates, PV cell and heat extractor, leading to higher T values, but in no case they will exceed 340 K).

Using the data of Fig. 6 for this temperature difference, we see that with traditional TEGs, one cannot expect additional electrical efficiency due to their usage larger than 1.5%; taking account of the heat flux losses on the way to TEG, the expected increase of electrical efficiency provided with this TEG model ($ZT = 0.7$) is around 1%. Calculations made with expression (4) for these temperature conditions agree with the number given. Taking in (4) the value of ZT equal to 2.4, we get essentially larger increase of electrical efficiency due to TEG (3.2%); with $ZT = 4$, the efficiency will be 4.1%. Thus, the use of existing traditional TEGs in the system studied cannot be really effective, but the advanced TEG might be useful.

4.2. TEG in concentrated sunlight

Experimental results of Section 3.2 show that traditional TEG with $ZT = 0.7$ could provide efficiency of 4% when $T_h = 200$ °C, $T_c = 50$ °C (473 and 323 K correspondingly, $\Delta T = 150$ K), and efficiency of around 6% at conditions: $T_h = 300$ °C (573 K), $T_c = 50$ °C (323 K), $\Delta T = 250$ K. Calculations using formula (4) confirm these data. On the other hand, TEG with $ZT = 2.4$, according to (4), will have efficiency of 12.4% in the first case (hot side at 473 K) and of 15.3% in the second one (573 K), whereas with $ZT = 4$, the corresponding efficiencies will be 13.45% and 19.3%. To make conclusion about an effect of their use, we should estimate the degree of concentration of solar radiation necessary for the TEG's normal performance, and the losses connected with the concentration.

On the basis of the value of TEG's thermal resistance R_{heat} given above, we calculate that to obtain $\Delta T =$ 150 K, the heat flux of 65 W is needed; with TEG's surface area of 16 cm^2, the corresponding flux density is 41 KW/m^2, whereas for $\Delta T = 250$ K it will be 70 KW/m^2. Since this heat flux will be provided by absorption of concentrated sunlight, with account of possible optical and thermal losses, we see that for the first case ($\Delta T = 150$ K) the concentration degree should be $C = 55$, and for the second one ($\Delta T = 250$ K, flux density of 68 KW/m^2) $C = 95$. The non-concentrated Sun radiation intensity we take as $I = 1$ KW/m^2. Our previous experiments with solar concentrator (Meneses-Rodrígues et al., 2004) show that

indeed, with concentration of 50 the temperatures above 200 °C could be easily obtained.

The optical quality coefficient α we take equal to 0.9 (it is defined by the reflectivity of mirrors used in concentrator, which could be easily prepared that good); thermal losses coefficient β, according to (5), will be 0.85 for the first case, and 0.8 for the second one (here, for simplicity, we take $k = 1$). Thus, the actual radiation intensity on TEG ($\alpha\beta CI$) will be 42 KW/m^2 in the first case, and 68.4 KW/m^2 in the second one, so that the normal working conditions for TEG will be provided. The concentration degree up to $C = 100$ can be easily obtained, either con mirrors or lenses (Fresnel lenses, in particular) and are not expensive; the corresponding Sun tracking system (see Vorobiev and Vorobiev, 2010) can also be made simple and non-expensive. Thus we see that TEG in concentrated sunlight could have conversion efficiency comparable to that of commercial PV panels; the cost of TEGs now is a little higher than that of PV modules of equal surface area, but taking account of essential reduction of TEG's area at concentration systems, we came to the conclusion that the actual cost of energy generated could be acceptable in the systems with TEGs discussed (see next section).

Another point is that all the systems with TEGs using concentrated as well as non-concentrated radiation, are the hybrid ones in a sense that they produced hot water (air) along with electrical energy, and the total amount of heat energy produced is determined, in the first approximation, by the total area of collection of solar radiation, i.e. is practically the same in all the systems discussed.

4.3. Hybrid systems with PVM and TEG

The systems shown schematically in Fig. 2b and c include both PVM and TEG and therefore promise higher efficiency than the systems discussed previously. In the first of them (Fig. 2b), the PVM works in concentrated light and at elevated temperature, which in turn defines the temperature of the TEG's hot plate. The efficiency of PVM decreases with an increase of temperature whereas the TEG's efficiency increases. So, there will be an optimal temperature corresponding to the maximum of electrical efficiency of the whole device and depending upon the parameters of its components.

We have seen (Section 4.1) that at temperatures not very high and under condition that PVM and TEG have good thermal contact, practically all heat generated in PVM under illumination is extracted by TEG. Taking the PVM temperature (T_h) as constant (i.e. neglecting the temperature gradient in it), we write for the electrical power generated by the PVM an expression:

$$P_e = \alpha\beta CI(1 - R)\eta_\alpha[1 - \gamma(T_h - T_a)]A \quad (7)$$

Here η_α is the PVM efficiency at room temperature (T_a) and the corresponding radiation concentration, and γ is the temperature coefficient of this efficiency. Then we assume that the heat extraction from TEG (element 4 in Fig. 2b) is so efficient that the cold plate temperature is equal to T_a. For additional electric power generated by TEG we shall have (using expression based on (1))

$$P^* = \eta^*\alpha\beta CI(1 - R)\{1 - \eta_\alpha[1 - \gamma(T_h - T_a)]\}A \quad (8)$$

The TEG's efficiency is given by (4). The total electric power generated will be given by the following expression:

$$P_{tot} = B\left\{\Delta T\frac{\sqrt{1 + ZT_M} - 1}{T_h\sqrt{1 + ZT_M} + T_a} + \eta_\alpha(1 - \gamma\Delta T)\left[1 - \Delta T\frac{\sqrt{1 + ZT_M} - 1}{T_h\sqrt{1 + ZT_M} + T_a}\right]\right\} \quad (9)$$

Here $B = \alpha\beta CI(1 - R)A$, and $\Delta T = T_h - T_a$.

In Fig. 7 we present the dependence upon ΔT of the efficiencies of PVM ($\eta_{PV} = \eta_\alpha\,[1 - \gamma\Delta T] = P_e/B$), of TEG ($\eta^*$) and of the total efficiency $\eta_{tot} = P_{tot}/B$, at concentration $C = 55$. For PVM we take the data corresponding to c-Si cell: $\eta_\alpha = 20\%$ (it takes account of sunlight concentration; the value for non-concentrated radiation is 16%), and $\gamma = -4 \times 10^{-3}\ \mathrm{K}^{-1}$ (Nann and Emery, 1992; Vorobiev et al., 2006a). We do not include here the data for a-Si, for two reasons: this cell usually is not used with concentrated light (i), and its temperature coefficient is much smaller than that for c-Si (ii), that makes it less interesting for investigation. For TEGs, we take all three options studied above: one with traditional material and $ZT = 0.7$, another with advanced materials, $ZT = 2.4$ and $ZT = 4$. Here the straight line 1 shows the PVM efficiency, three growing lines (2–4) show efficiency of TEG (the higher is ZT value, the higher goes the curve); the last three curves (5–7) show the total efficiency (again, the higher curve corresponds to the higher ZT value). We see that for the system with highest ZT value (equal to 4) the total efficiency has a maximum at about 100 K of temperature difference, and the total efficiency is higher than the efficiencies of the

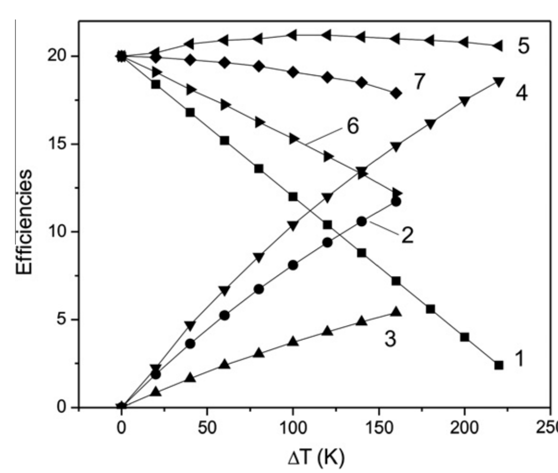

Fig. 7. Calculated dependence upon the temperature difference between the TEG's plates ΔT of the efficiency of PVM (1), of TEG with different figure of merit ($ZT = 2.4$ for curve 2, 0.7 for curve 3 and 4 for curve 4), and of the total efficiency with different TEGs (curve 5 for $ZT = 4$, 6 for $ZT = 0.7$ and 7 for $ZT = 2.4$).

system's active elements acting alone. In cases of lower figures of merit of TEG, the total efficiency has a maximum at $\Delta T = 0$, but addition of TEG widens the working temperature interval of the system, thus making it more stable in relation to fluctuations of temperature.

In relation to the hybrid system shown in Fig. 2c, we discuss both types of PVM (c-Si with efficiency of 16% and a-Si with efficiency 10%, both values are generally accepted), using the results published by Vorobiev et al. (2006a), in relation to the part of the total solar energy flux that passes through the cell (we call it "thermal" part of the solar spectrum). This part is determined by the value of band gap, and for c-Si (gap of 1.1 eV) it is 20 %, whereas for a-Si (1.6 eV) – 50%. Taking into account the reflection losses of 10% with antireflection coating (no other losses are counted, i.e. the PVM should have transparent electrodes and the substrate), we get finally 18% for "thermal part" with c-Si and 45% with a-Si.

To obtain proper working conditions for TEG, we use results of Section 4.2: to provide temperatures $T_h = 200$ °C (473 K) and $T_c = 50$ °C (323 K), the 55 times concentration of total sunlight is necessary, and for temperatures 573 and 323 K – 95. Having smaller energy flux after the PVM in this system, we have to increase the value of C, namely, in $100/18 = 5.55$ times for c-Si, and $100/45 = 2.22$ times for a-Si. It gives values of $C = 305$ and 527.5 for lower and higher temperatures in case of c-Si, and $C = 122$, $C = 211$ for a-Si. Evidently, the use of c-Si in this system is not practical, since the concentration necessary is too high. For a-Si the concentrations are reasonable, but it is also necessary to take into account, that the conversion efficiency of TEG calculated in 4.2 now refers only to the "thermal" part of radiation flux. So, in the most interesting case (higher temperature, advanced material) the TEG's efficiency in case of $ZT = 2.4$ related to total solar radiation, will be $15.3\% \times 0.45 \approx 7\%$, and with $ZT = 4$, it will be $19.3\% \times 0.45 = 8.7\%$. Therefore, the corresponding total hybrid system efficiency in this case will be 17% or 18.7%. Thus we see that this system can be quite efficient with PVM made of semiconductor with higher band gap (like CdSe, 1.7 eV), using TEG with advanced materials. Table 1 summarizes some important parameters of two concentrated systems (the third one is fully represented by Fig. 7, and the system without concentration is not practical with existing elements); $\eta_{0.7}$ and $\eta_{2.4}$ are the efficiencies corresponding to $ZT = 0.7$ and $ZT = 2.4$.

All estimations made in this section refer to the maximum intensity of solar radiation (midday summer conditions for northern hemisphere). It is evident that daily and seasonal variations of the irradiance will affect the performance of the systems studied. This point is discussed below.

Table 1
Efficiency of TEG-based concentrator systems for maximum irradiance.

System	Concentrator – TEG		PVM – concentrator – TEG	
PVM	–	–	a-Si	a-Si
ΔT (K)	150	250	150	250
C	55	95	122	211
$\eta_{0.7}$ (%)	4	6	–	–
$\eta_{2.4}$ (%)	12.4	15.3	15.6	17

5. Comparison of basic characteristics of photovoltaic and thermoelectric converters

5.1. Effect of variations of solar radiation intensity upon PVM and TEG performance

PVM and TEG have very much in common: both as a rule are semiconductor p–n devices without moving parts, without vacuum and practically without necessity for maintenance, with useful lifetime of 20–30 years proven experimentally. Their energy generation is ecologically clean, so both are perfect candidates for the future sustainable world. There is, however, one essential difference in relation to performance at different irradiation: PVM has efficiency independent upon the intensity of solar radiation, so its energy production is linear function of irradiance, whereas TEG's efficiency directly depends upon irradiance (i.e. on the temperature difference over the device that is in almost liner relation with irradiance), so the energy generated is approximately quadratic function of irradiance, leading to lower parameters at lower irradiance. Here we discuss the actual effect of these factors.

For qualitative estimations of the effects of irradiance variations we shall use the results of investigation published by Vorobiev et al. (2005), where a modeling was made of absorption and scattering radiation processes in atmosphere giving the dependence of solar radiation intensity I upon angular position of Sun in relation to zenith (angle φ) that agrees with the main reference points (AM0, AM1, AM1.5 and AM2) with accuracy better than 5%. The corresponding expression is

$$I = I_C \exp[-(a_S/acos\varphi)(1 - 1/Racos^2\varphi)] \tag{10}$$

Here I_C is cosmic solar radiation (AM0), a_S is atmospheric absorption/scattering coefficient at the Earth's surface, R is radius of earth, and a – analogue of barometric constant (a_S and a are used as adjusting parameter); the corresponding calculated dependence $I(\varphi)$ is shown in Fig. 8 (squares; the asterisks show the corresponding reference points). To verify experimentally this dependence (Vorobiev et al., 2005), we use the measurement in Queretaro, Mexico, having northern latitude of 20°; during summer solstice the midday position of Sun is practically vertical (the actual $\varphi = 20{-}23° = -3°$), so that horizontally placed PVM has maximum irradiance ($\cos 3° = 0.998$). With daily variation of the angular position of Sun, the irradiance of Sun tracking PVM follows the upper curve of Fig. 8, from right to left and back. The irradiance of non-tracking PVM with ideal orientation (i.e. normal to the radiation flux at midday) for each Sun position is defined by the corresponding value of the upper curve

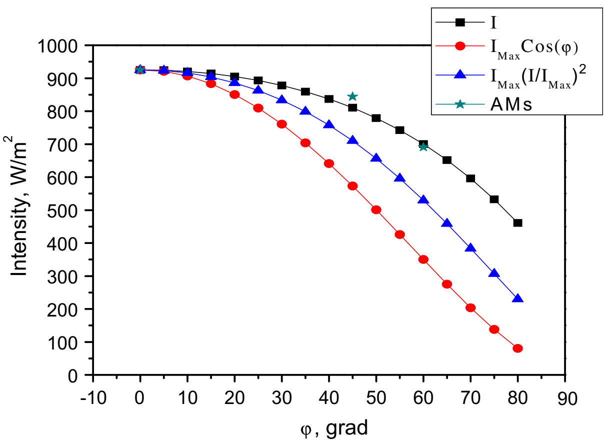

Fig. 8. Calculated dependence of irradiance upon Sun position for tracking PVM (1), for stationary ideally oriented PVM (2) and for Sun tracking concentrated TEG system (3).

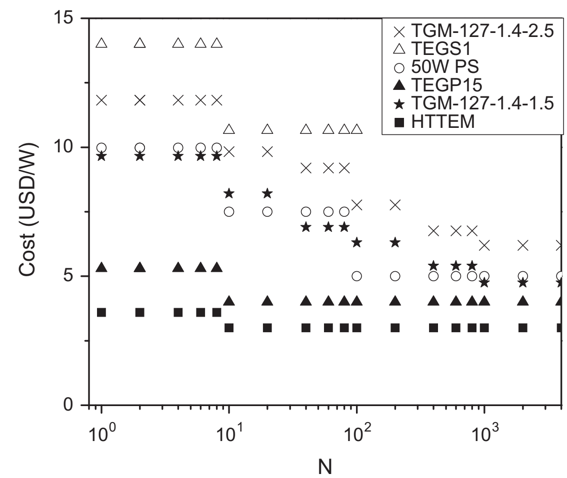

Fig. 9. Cost of electric energy production by different TEGs.

multiplied by $\cos\varphi$ (circles). Thus the upper and the lower curves represent daily variations of energy production by tracking and non-tracking PVM.

Taking for TEG the quadratic dependence of energy production upon irradiance, we get for characterization of daily variations for any concentrating system with TEG (Sun tracking, there are no others) the curve of Fig. 8 presenting the angular dependence of $I_{\mathrm{Max}}(I/I_{\mathrm{Max}})^2$ (triangles). Here I_{Max} is the maximum of irradiance at $\varphi = 0$. Thus we see that the total energy generated during the day by hybrid system with TEG is somewhat lower than that for Sun-tracking PVM with equal maximum power generation, but is higher than for stationary PVM with ideal orientation towards the Sun. Similar estimations could be made for any geographical point, although it is evident that TEG-based systems are more efficient in places with high solar irradiance.

5.2. Cost-efficiency aspects

The materials and technology of TEGs are not more expensive and complicated than those of a standard PVM, and the difference in prices is determined by the actual demand and the bulk of production (the great demand for PVMs observed during the last decade has caused considerable reduction of their prices which now an average is around 4 US dollars per watt-peak of power generated). The traditional hybrid PV/Thermal systems are approximately 50% more expensive than PVMs used in them: the typical numbers (SOLIMPEKS, 2011, Turkey) for hybrid system based on c-Si PVM are 6.4 USD per watt of electric energy and 2.5 watts of thermal energy; the other data are: \$11USD/($W_{el} + 4.5W_{th}$), Carbon Free Group of Great Britain <www.carbonfreegroup.com>, and \$8USD/($W_{el} + 6.5W_{th}$), Millennium Solar, Israel, <www.milleniumsolar.com>.

In Fig. 9 we attempted to show the price of energy produced by different TEGs (TGM's are of Kryotherm, Russia, the rest of the TEG Power Company, USA, <www.tegpower.com>) as function of the number of devices N. Reasonably enough, the price decrease with the number. It could be seen that if one employs industrial number of devices (around 1000 or more), the cost will be practically the same as it is now for the case of PVM, i.e. approximately 4 USD/W. Since the heat extraction is indispensable element of the TEG's performance, thermal energy is always produced along with electric energy. Due to relatively small size of TEG, the corresponding system is essentially simpler than that used is traditional PVT (see reviews by Zontag (2008), and Ibrahim et al. (2011)), so one could expect that the total cost of the hybrid system based on TEGs, including the Sun tracking system, will be higher than the actual price of TEGs by not more than 50%, same as in traditional systems (estimations of possible cost of tracking system could be found in papers by Vorobiev and Vorobiev (2010)).

With smaller electric efficiency of existing commercial TEGs compared to PVMs, the ratio of thermal-to-electric energy production in TEGs-based hybrid systems will be larger than that in traditional PV/Thermal systems: we saw that for the latter, this ratio varied between 2.5 and 6.5. In case of the system with TEG in concentrated solar radiation working at $T_h = 200$ °C (see discussion in Section 4.2) this ratio will be more than 10, decreasing down to 6–8 if the higher temperatures are employed for TEG's performance.

The cases of systems using both TEGs and PVMs and working in concentrated radiation (Section 4.3) are difficult to analyze in details at this stage. However, we could say that if both components have comparable cost, and the efficiencies are approximately summed, the final cost of the energy produced will be quite acceptable, as it was shown for the case of the TEG alone.

6. Conclusion

The hybrid solar systems with TEG can be considered useful and economic, especially in countries with high

insolation, like Mexico, India or China; the comparison of Sun-tracking concentrating TEG-based hybrid system with traditional PV/Thermal system using Photovoltaic Module PVM shows that both have comparable cost and thermal efficiency. The electrical efficiency of PVM-based system today is higher than that for TEG-based one, but the expected development of advanced nanostructured materials with higher thermoelectric figure of merit could make these efficiencies practically equal. On the other hand, the tracking system for TEG could be essentially simpler and cheaper than that for PVM, whereas the non-tracking PVM will have lower daily energy production than the tracking TEG with similar peak efficiency.

The inclusion of TEG in hybrid concentrating system with PVM operating at high temperature will enhance the thermal stability of system's electrical efficiency reducing its loss with an increase of temperature. Another TEG-based system with concentration of the radiation passing through PVM will be efficient and economic, if new types of PVMs will be developed, based on semiconductors with band gap essentially larger than that in c-Si used in major part of today's commercial PVMs, and having neither absorption nor scattering of photons with energies below the band gap.

Acknowledgements

The authors want to acknowledge the financial support of CONACYT (project No. 48792) as well as the great help and encouragements of Irina Lymar and Peter Shostakovsky from KRYOTHERM Company. E.A. Chávez-Urbiola would like to thank CONACYT for his scholarship.

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